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Facilitated Visual Search at Low Color Contrast

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Abstract. The influence of color contrast on visual search behavior was analyzed in young and old observers with normal vision and observers with age-related macular degeneration. A display of a variable number (2 or 8) of 2.7 deg disks, arrayed on a virtual circle of 12 deg diameter, was presented to the observer. The task was to indicate as rapidly as possible whether one disk was a different color than the other(s), which was true on 50% of the trials. The color difference was chosen randomly from one of 4 color axes (achromatic, protan, deutan or tritan confusions axes) and from one of three contrasts along each of these axes. A significant interaction between stimulus contrast and number of distractors was found in the observers with an intact central visual field. Surprisingly, the source of this variation was a decrease in reaction time with increase in the number of distractors at the lowest contrast levels tested. Though not significant, a similar tendancy was noted throughout the reaction time data in the low vision group. As the 8-disk stimuli formed a circle, proximity or configuration effects might explain this unexpected result. In the normal groups, reaction time as a function of separation of the 2-disk stimuli, however, did not consistently vary as the first of these two hypotheses would predict. In contrast, the average reaction time did increase with separation of the disks in observers with macular degeneration, suggesting that spatial uncertainty constrains their search times.

1 Introduction

Color vision deficiencies are traditionally evaluated with respect to the capacity to discriminate color differences (or contrasts) along various axes in a color space. For example, most color vision tests are based on the cone-isolating axes, otherwise known as the dichromatic confusion axes, because observers lacking a particular class of cone photopigments cannot discriminate among lights that fall along such an axis. The question asked is: Along what color axes is the observer least sensitive to color differences? In evaluating observers with low vision, one would like to know as well what are the stimulus characteristics that permit performing a task with maximal efficiency. For example, one can ask what is the minimal contrast or size of letters that allow an observer to obtain his maximal reading rate. There are several studies that have evaluated the functional role of color in reading[1,2]]brighness perception[3] and object and scene identification[4,5].

We have begun to evaluate the role of color contrast in visual search in observers with low vision. In a typical experiment, the reaction time to detect the presence of a target stimulus is measured as a function of the difference between the target and the distractors. Two types of behavior have been observed[6]. In the first case, the reaction time increases as the number of distractor elements increases. This result is sometimes referred to as serial search because the observer has to look individually at each stimulus element to decide if it is the target or not. In the second case, the reaction time is independent of the number of distractors. This result is sometimes referred to as parallel search because it is as if the observer can process all of the stimuli without having to attend to the individual elements.

This task is interesting from the perspective of low vision because it can engage part or all of the visual field. Nagy and Sanchez[7] have observed that observers show serial search behavior at low color contrasts but switch to parallel search at some critical contrast. Thus, the question that we would like to pose is whether observers with visual field defects can integrate color differences across the visual field in a parallel fashion and if so, what is the minimum contrast necessary to do so. We present here some initial results from normal and low vision observers that were unexpected.

2 Methods

2.1 Stimuli

Stimuli were generated with a VSG/2 color graphics board (Cambridge Research Systems) in a pentium computer and displayed on an EIZO FlexScan T562-T color monitor (24 x 33 cm) run at a frame rate of 120 Hz. Luminances were calibrated with the OPTICAL system (Cambridge Research Systems) and chromaticities measured with a CS-100 chromameter (Minolta). The screen was set to a neutral gray background with luminance 65 cd/m^2 and chromaticity $(0.294, 0.303)$ for the CIE 1931 standard observer.

2.2 Procedures

On each trial a display of 2 or 8 disks, each of 2.7 deg diameter was presented on a virtual circle of 12 deg diameter. The task was to respond as rapidly as possible if one disk was a different color than the other(s) which was the case on 50% of the trials. The color difference between the disks was chosen randomly from one of four color axes—achromatic, protan, deutan or tritan confusion axes—through the background color and from one of three pre-defined contrasts along each of the axes. The two colors chosen straddled the color axis with respect to the background color. Thus, if the distractors along the deutan axis were chosen as a certain modulation of the background color in the blue-green direction, the target was chosen to be an equal modulation in the complementary, magenta direction. The Michelson contrasts calculated between the target and the distractors were nominally chosen as 0.25, 0.5 and 0.75 of the maximum contrast available on each axis. Along the protan, deutan and tritan confusion axes, the maximum cone contrasts available were calculated to be $(L_{\max}, M_{\max}, S_{\max}) = (0.14, 0.16, 0.84)$, respectively, with respect to Judd's modification of the 1931 CIE standard observer. A third response button was available if the subject detected no disks, which would occur if the patient was a dichromat and the colors fell along his confusion axis, or if he had a loss of contrast sensitivity. These trials were noted but did not contribute to the analyses.

The observer viewed the display monocularly from a distance of 57 cm. There were 48 different stimulus combinations (4 axes, 3 contrasts, present/absent, 2/8 stimuli), repeated in 4 random sequences.

2.3 Subjects

All observers were given ophthalmological exams and performed with the best optical correction for the testing distance. Color vision was screened for gross defects with the PV-16 (Precision Vision), an enlarged panel D-15. Eight young observers (mean age = 32 ± 6 years) and 7 older observers (mean age = 65 ± 11 years) participated in the study. In addition, 4 observers with exudative age-related macular degeneration (AMD) were tested (mean age = 76 ± 3.3 years, acuities ranged from 0.04–0.4, absolute scotomata in the central 10 deg were on the order of 5 deg diameter). Two of these observers showed a single crossing on the PV-16 in the tritan direction. A third observer inverted a pair of caps along the tritan direction. The fourth observer produced a series of crossings along the scotopic axis.

3 Results

In our initial evaluation of the data from the AMD patients, we noted that despite a great deal of variability, for the majority of conditions, the reaction time decreased with an increase in the number of distractors. An analysis of variance indicated that the effect of number of distractors was not significant ($F(1,3) = 1.16$, $p = 0.36$), even though the reaction time decreased on average by about 100 msec between 2 and 8 distractors. Patients with AMD do not form a homogeneous sample, having different degrees of field loss, different losses of visual acuity, etc. Thus, the size of our sample is probably too small to come to a secure conclusion. These preliminary results, however, motivated us to evaluate young and old observers with intact visual fields to determine the influence of the number of distractors on reaction time under our stimulus conditions.

For both the young and old groups, the average reaction time decreased with an increase in the number of distractors (young: 34.5 msec, $F(1,7) = 5.901$, $p = 0.046$; old: 99.5 msec, $F(1,6) = 5.415$, $p = 0.059$). These results only hover about the significance level even though they indicate the same tendancy as shown by the AMD group.

Figure 1 shows the interaction between number of distractors and contrast level for the young and old groups. This interaction was significant for both groups (young: $F(2,14) = 4.80$, $p = 0.029$; old: $F(2,12) = 4.98$, $p = 0.023$) due, as the left hand figure suggests, to a decrease in reaction time with an increase in number of distractors at the lowest contrast level (young: $F(1,7) = 7.86$, $p = 0.031$; old: $F(1,6) = 8.66$, $p = 0.02$). At the lowest contrast level, the largest effects were obtained on the protan and deutan confusion axes with average decreases of 104 msec and 308 msec for young and old groups, respectively. Along the achromatic axis, the reaction time only decreased by 8 msec for the young group and increased by 1 msec in the old group. Decreases in reaction time were found along the tritan axis at the lowest contrast but these were only half as large as those along the protan and deutan axes.

The lowest contrast levels tested (25% of the maximum along each axis) on the protan and deutan axes corresponded to cone contrasts of 0.035 and 0.04, respectively, suggesting the possibility that the facilitation in response time observed is related to contrast level. Indeed, observers with AMD are likely to have reduced chromatic contrast sensitivity which would reduce the effectiveness of higher contrast stimuli. If this were the case, one would expect the AMD observers to perform at all contrasts more similarly to the normal observers at low contrast. But, it would not explain why reaction time would be facilitated with more targets at lower contrast levels.

One possibility is related to the configuration of the stimuli. In the 8-stimuli condition, the configuration of the disks formed a circle. This coherent figure could have aided visual search. The target would have appeared as a gap in the circle. In the 2-stimuli condition, the disks fell on the same virtual circle, but their positions were randomly chosen. No specific configuration then would be associated with the 2-stimuli conditions. On the other hand, in that condition, the observer has to both locate and compare the disks to evaluate if they are the same or not. Thus, an alternative explanation is that at low contrasts spatial uncertainty hindered visual search.

The spatial uncertainty hypothesis would predict that the reaction time would depend on the spatial separation of the disks. When the two disks were adjacent on the circle, it would be easier to compare them than if they were at more separated positions. We reanalyzed the search times of the young, old and AMD patients for the 2-stimuli condition as a function of separation on the circle. There are 8 places on the circle, so that the ordinal separation between the disks can vary between 1 (adjacent) and 4 (on antipodes of the circle).

Figure 2 shows the median reaction times for the young, old and AMD groups as a function of ordinal separation of the 2 disks. For both groups of observers with an intact central visual field, the reaction time is independent of the separation despite overall differences due to age. Thus, spatial uncertainty would not seem to explain the decrease in reaction time with increase in number of distractors in this group. On the contrary, the reaction times for the AMD patients increase systematically with ordinal separation, suggesting that spatial uncertainty does play a role in their visual search behavior.

4 Discussion

Decreases in reaction time with increases in the number of distractors have been previously observed over a similar range of stimulus set sizes[8,9]. In an extensive set of experiments, Bacon and Egeth[8] demonstrated that such facilitory effects depended on the configuration of the distractors and not their relation to the target. In the present study, the fact that spatial uncertainty could not account for an increase in reaction time with 2-stimuli in observers with intact central vision leaves open the possibility that the decrease in reaction time with 8-stimuli was due to the configuration.

In the current experiments, such an effect seems to predominate only at low contrast levels. Perhaps, such configuration effects are subtle and only when the salience of the color differences is reduced, do they contribute significantly to behavior. It is interesting to note that in the cortex, feedback circuits enhance the response of cells to a target on a complex background of similar stimuli only at low contrasts[10].

The fact that the search behavior of observers with a central scotoma does seem to be limited by spatial uncertainty would suggest that, at least under our stimulus conditions, they were not able to integrate the color differences present in the visual field in a single glance. Indeed, some of the observers remarked that, in general, in order to interpret a visual scene, they must consciously look around to build-up an image of it. Their much longer reaction times are consistent with this hypothesis, as well.

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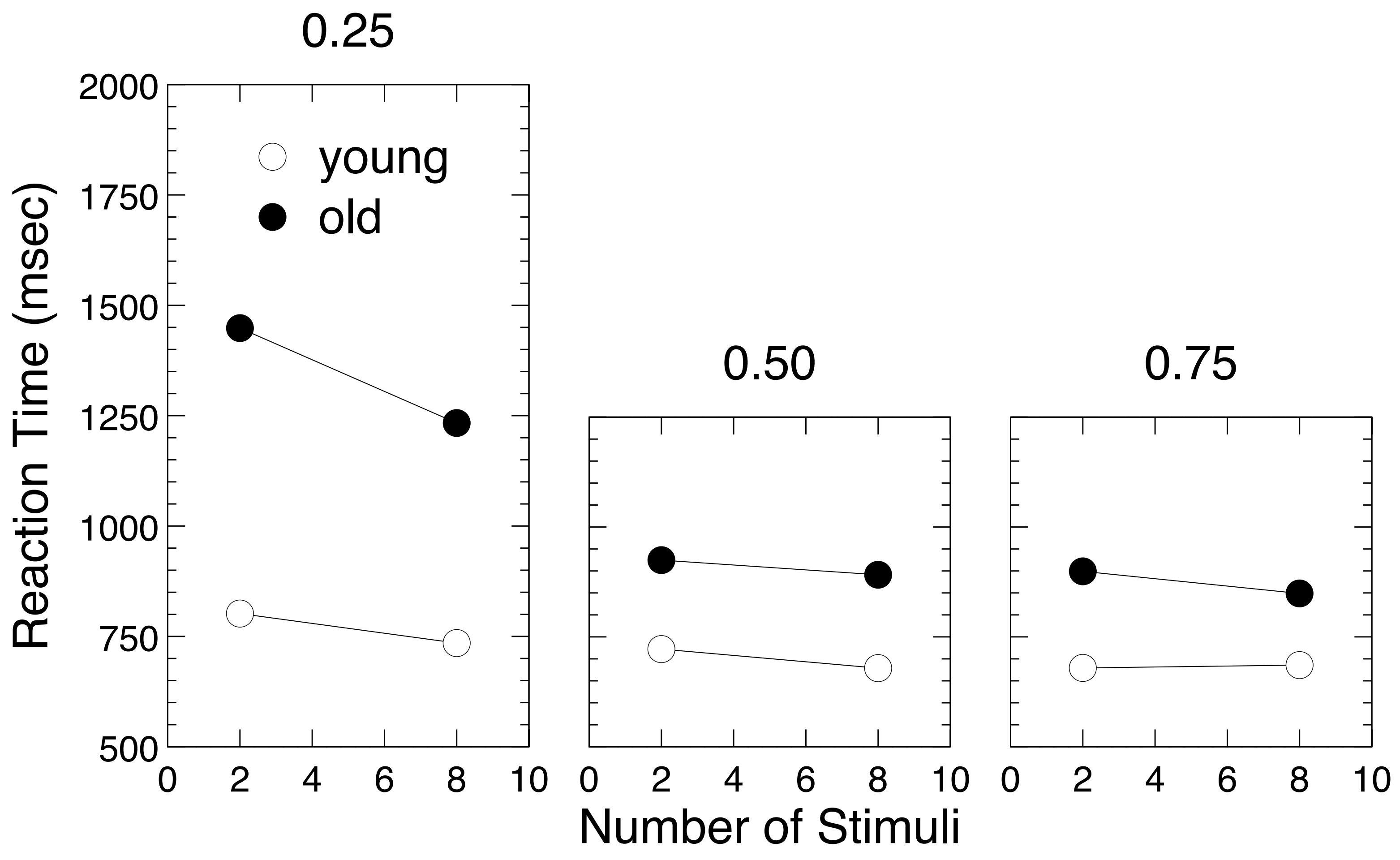
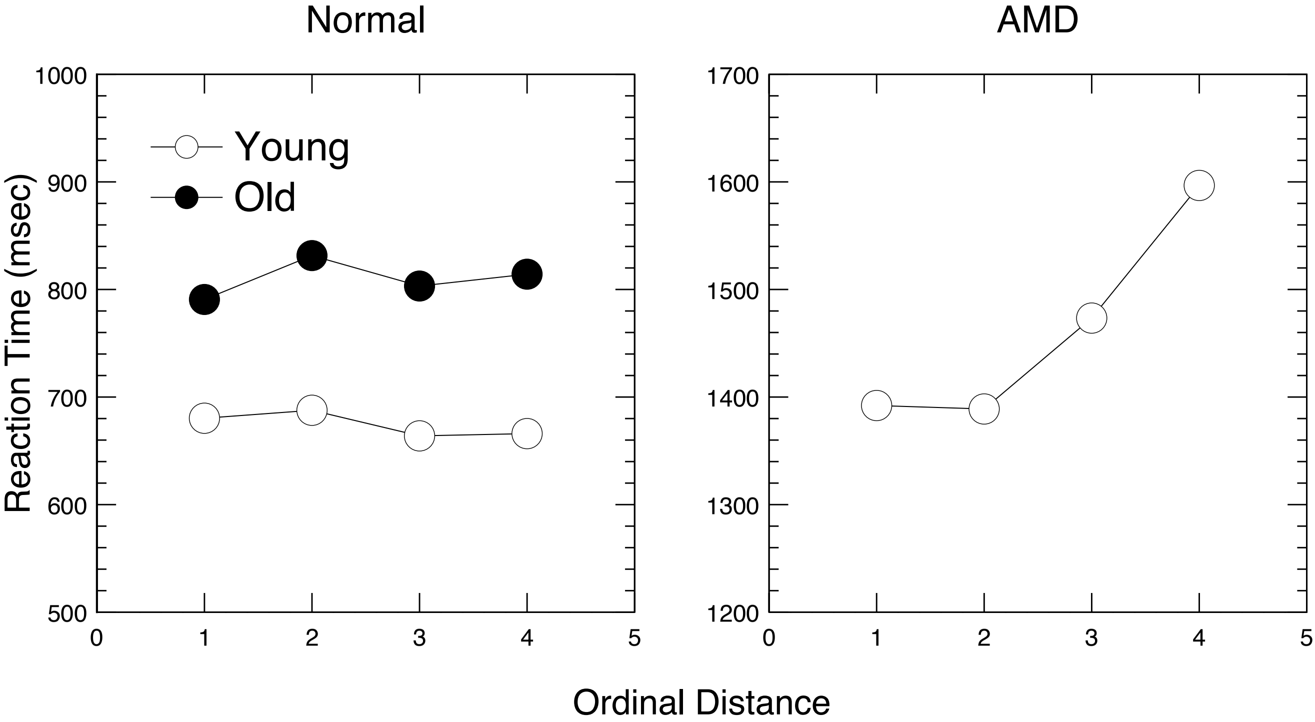
Figure Captions

Figure 1. Reaction time in milliseconds is plotted as a function of the number of stimuli in the display for each of the three nominal contrast levels used in the experiment, indicated at the top of each graph. The open symbols are the marginal means from the ANOVA for the young observers. The solid symbols are for the old observers.

Figure 2. Reaction time in milliseconds is plotted as a function of the ordinal separation around the circle for the stimulus configurations with only two stimuli. The graph on the left indicates the results from observers with intact central vision. The open symbols represent the young observers and the solid symbols represent the old observers. The graph on the right indicates the results obtained from the group of observers with AMD.


0.25
0.50
0.75
young
old
Reaction Time (msec)
2000
1750
1500
1250
1000
750
500
0
2
4
6
8
10
Number of Stimuli


Normal
AMD
Young
Old
Reaction Time (msec)
1000
900
800
700
600
500
1700
1600
1500
1400
1300
1200
0
1
2
3
4
5
Ordinal Distance